

$\Psi$



# New Results from a CEvNS Search with the CENNS-10 Liquid Argon Detector

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Fermilab Joint Experimental-Theoretical Physics Seminar

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# Overview

1. Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
2. COHERENT at the Spallation Neutron Source and First observation of CEvNS on CsI target
3. CENNS-10 Detector and First detection of CEvNS on Ar target
4. Future COHERENT Liquid Argon (LAr) – Towards CENNS-750
5. Summary



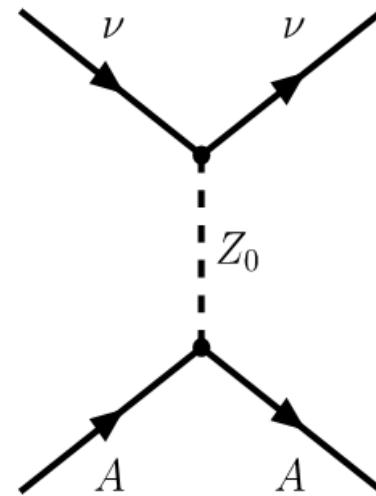
# Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

# Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- First mentioned by Freedman in 1974
- Neutrino interacts via neutral current with all nucleons in target nucleus
  - Initial and final states of the nucleus are identical
  - Neutral current, all flavors participate
- For large nuclei,  $E_\nu < 50$  MeV to meet coherence condition
- De Broglie wavelength for 50 MeV neutrino

$$\lambda = \frac{h}{p} = \frac{1200 \text{ MeV fm}}{50 \text{ MeV}} \sim 25 \text{ fm}$$

- Compare to  $\sim \text{fm}$  ( $10^{-15} \text{ m}$ ) nuclear radius



PHYSICAL REVIEW D

VOLUME 9, NUMBER 5

1 MARCH 1974

## Coherent effects of a weak neutral current

Daniel Z. Freedman  
National Accelerator Laboratory, Batavia, Illinois 60510  
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790  
(Received 15 October 1973; revised manuscript received 19 November 1973)

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

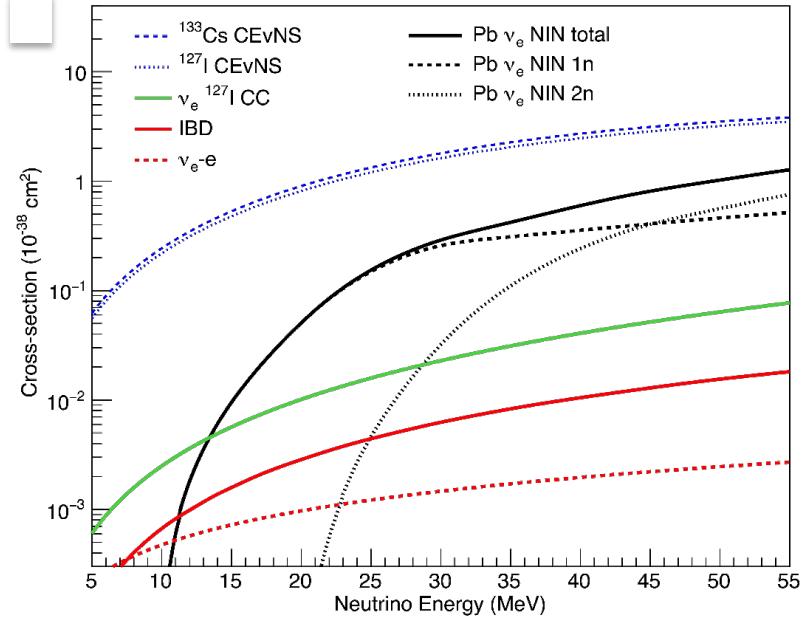
D.Z. Freedman, Phys. Rev. D 9 (1974)

V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

# CEvNS cross section

- CEvNS cross section is largest neutrino cross section (<100 MeV) on heavy nuclei
- Via coherence of recoil and near-zero weak charge of proton, cross section takes on distinct  $N^2$  dependence
  - $N$  is number of neutrons in target nucleus

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$



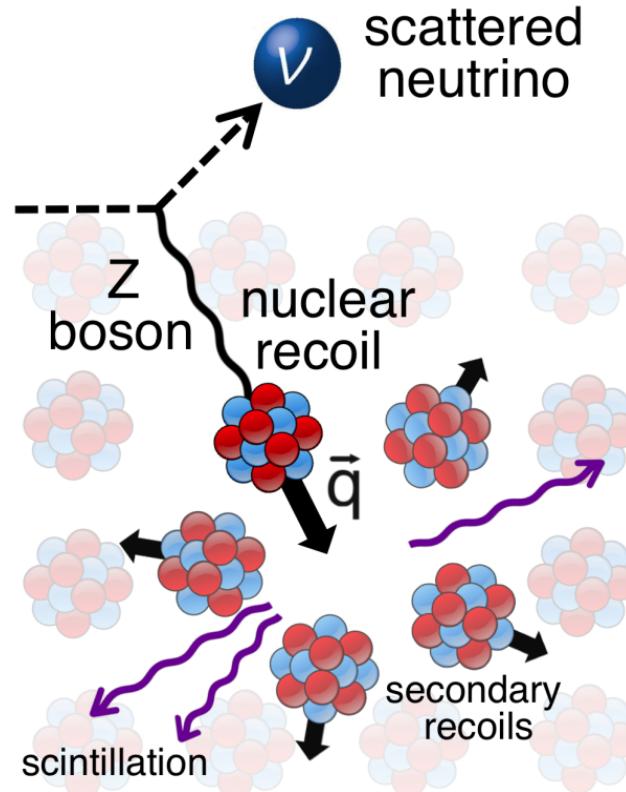
D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)

# Why is CEvNS hard to detect?

- Cross section is large for a weak-nuclear interaction
- Very-low energy nuclear recoils

$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV} \quad \text{For 50 MeV neutrino}$$

- Detector needs low detection energy threshold!
- Background rejection paramount!

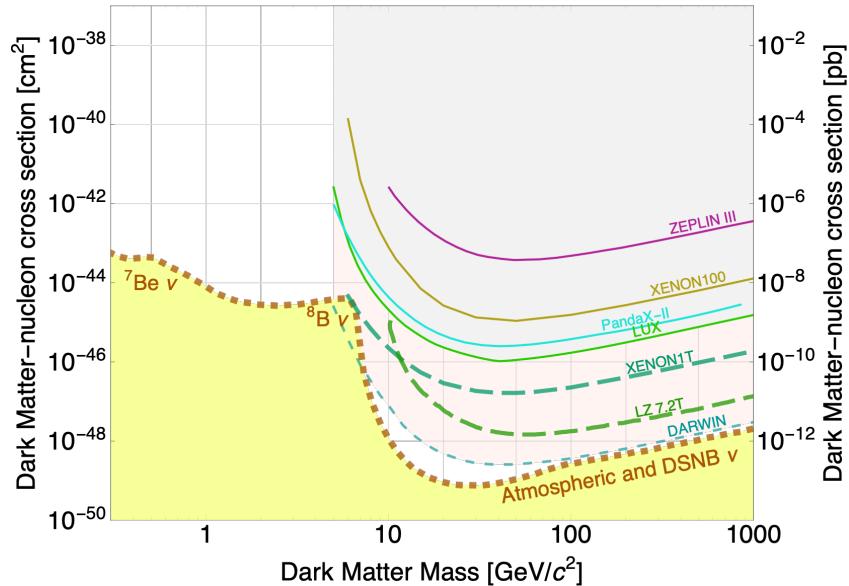


D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)

# Physics Implications

$$\frac{d\sigma}{dE} = \frac{G_F^2}{2\pi} [(1/2 - 2\sin^2\theta_w)Z - (1/2)N]^2 \left(1 - \frac{ME}{2E_\nu^2}\right) F(Q^2)^2$$

- Measurement of  $\sin^2(\theta_W)$  at low momentum transfer
- Neutrino electromagnetic properties
- Physics Beyond the Standard Model
  - New mediators and non-standard interactions
  - Background to Dark Matter searches
  - Accelerator-Produced Dark Matter
- Reactor Monitoring
- Nuclear Structure
- Supernova Neutrino (SN) physics



<http://cdms.berkeley.edu/limitplots/>

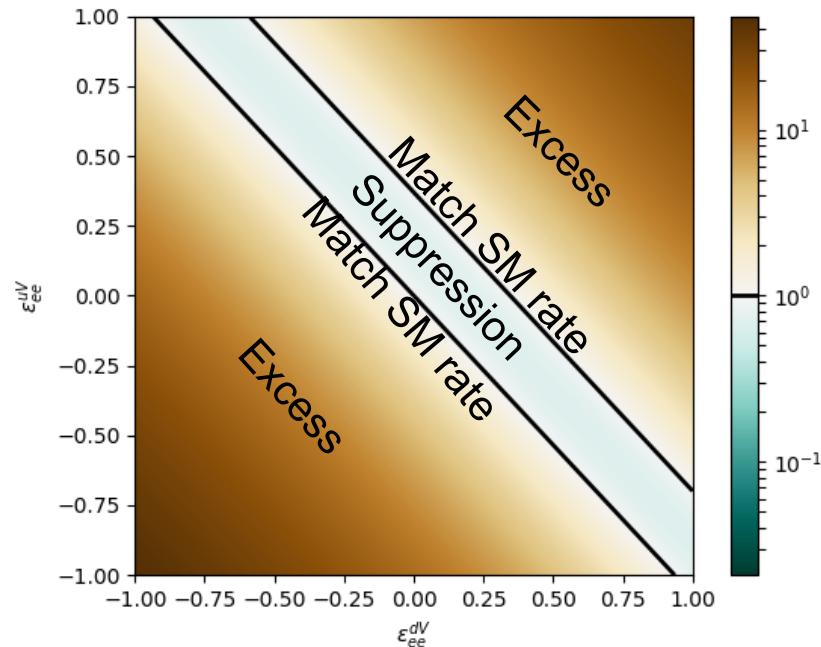
# Non-standard interactions (NSI)

- Addition to SM Lagrangian

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

$$Q_W^2 \rightarrow Q_{\text{NSI}}^2 = 4 \left[ N \left( -\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV} \right) + Z \left( \frac{1}{2} - 2\sin^2 \theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV} \right) \right]^2 \\ + 4 \left[ N(\epsilon_{e\tau}^{uV} + 2\epsilon_{e\tau}^{dV}) + Z(2\epsilon_{e\tau}^{uV} + \epsilon_{e\tau}^{dV}) \right]^2.$$

- Modifies weak charge
- NSI manifest as scaling of expected CEvNS cross section
- CEvNS sensitive to both non-universal and flavor changing neutral currents

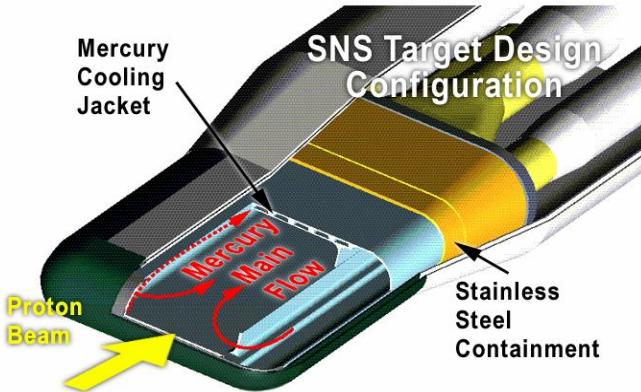


J. Barranco *et al.*, Phys. Rev. D 76 (2007)

J. Billard, J. Johnston, B. Kavanagh, arXiv:1805.01798

# **COHERENT at the Spallation Neutron Source and First observation of CEvNS on CsI target**

# The Spallation Neutron Source (SNS) at ORNL



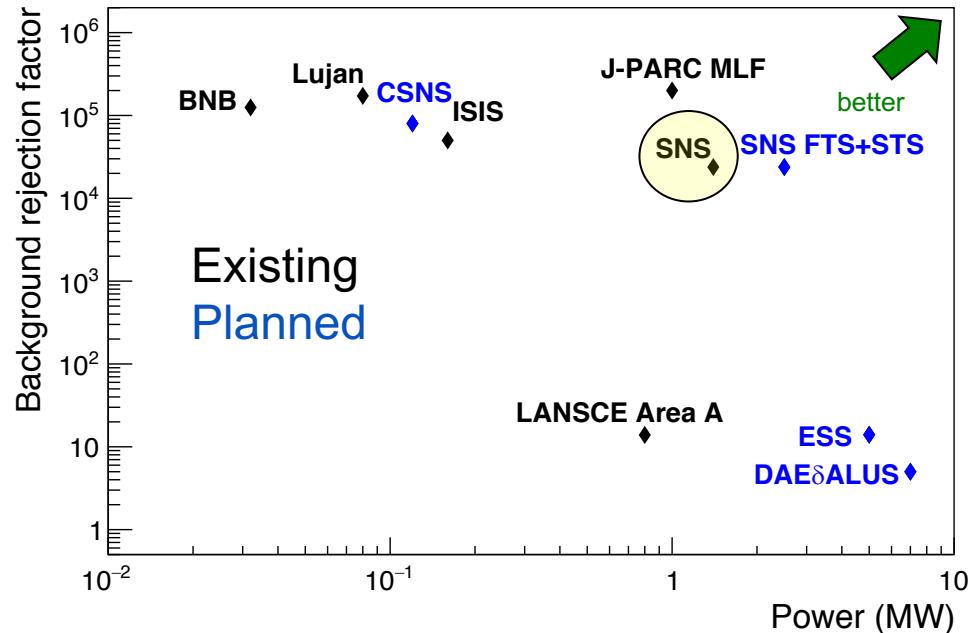
- Currently world's most powerful pulsed proton beam
  - Proton collisions with mercury create neutrons
    - AND neutrinos!



Images from [neutrons.ornl.gov](http://neutrons.ornl.gov)

# Why SNS?

- Multiple accelerators around the world
  - SNS has best combination of
    - Beam power - 1.4 MW
    - Background rejection through 60 Hz, 350 ns FWHM pulsed beam



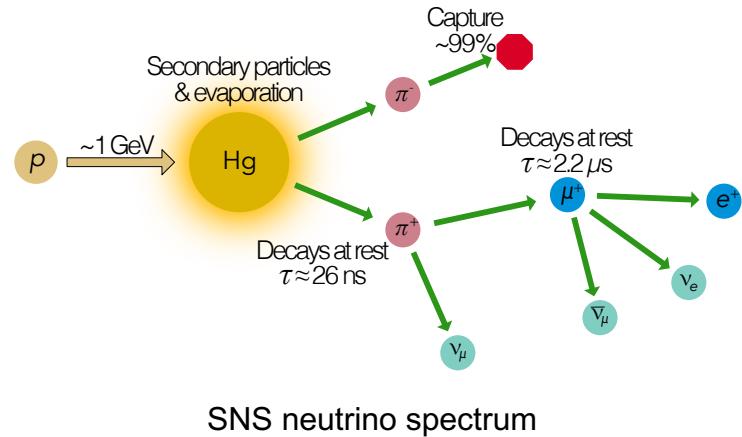
# SNS as a Neutrino Source

- p-Hg interactions also produce pions at a rate of ~0.09 pions/proton in addition to neutrons
  - Pions then decay at rest and produce muon and neutrino (“prompt”)
  - Muon decays at rest and produces two other neutrinos (“delayed”)

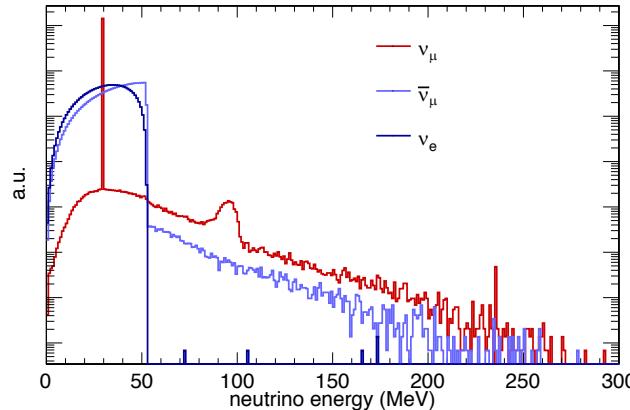
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{Prompt } 29.9 \text{ MeV } \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Delayed, spectrum from 3-body decay



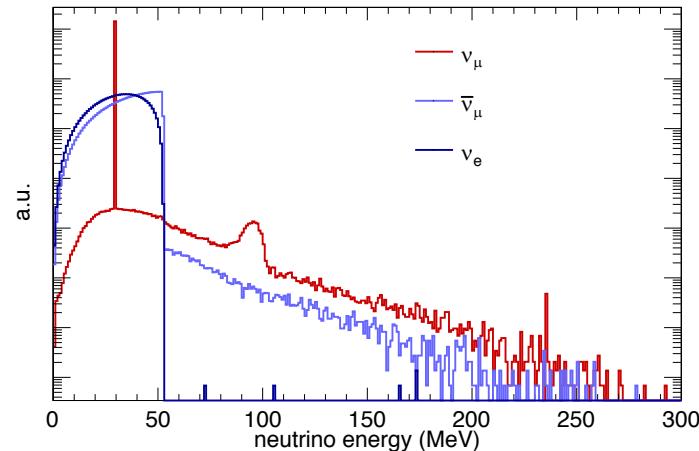
SNS neutrino spectrum



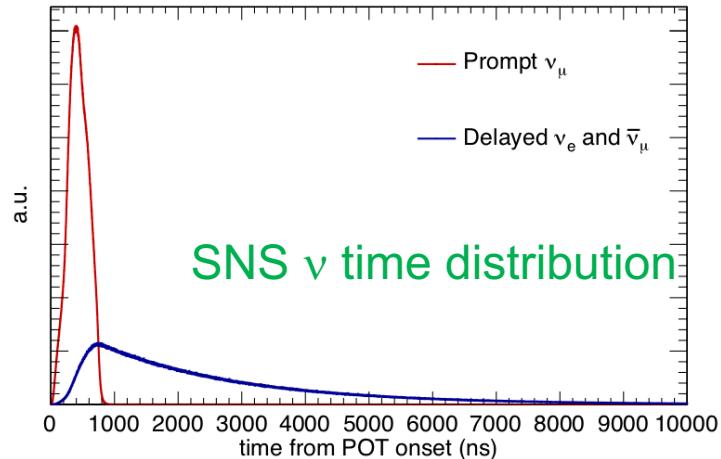
# SNS as a Neutrino Source

- Neutrino flux  $\sim 1 \times 10^7 \nu/\text{flavor}/\text{cm}^2/\text{s}$  at 20 m from target
- 1% decay in flight component
- $\sim 2 \times 10^{23}$  protons on target (POT)/year with routine operation at 1.4 MW!

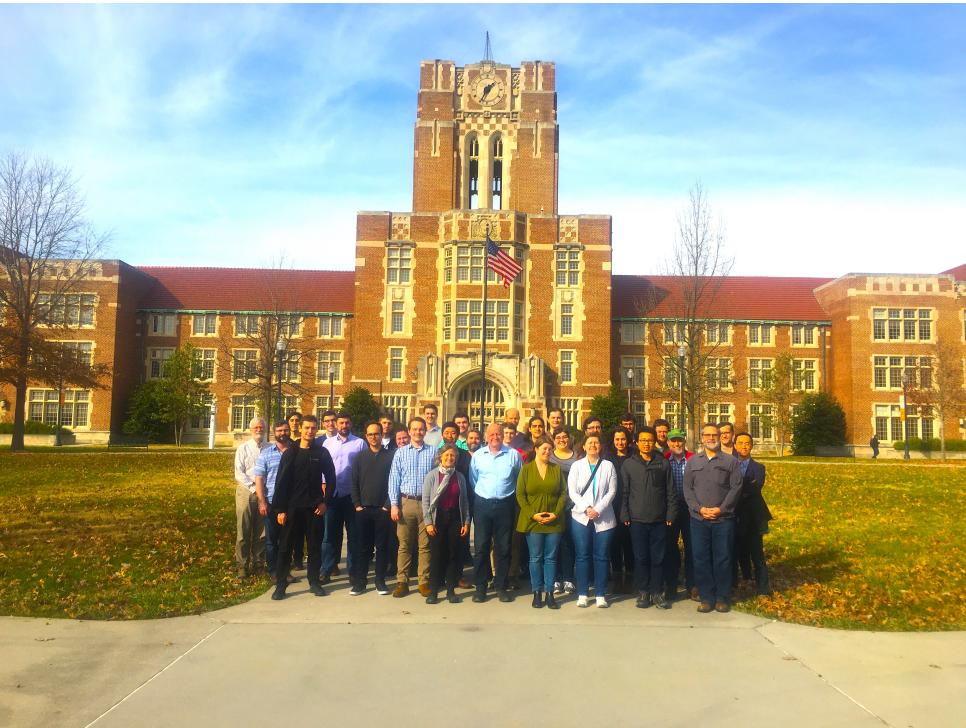
SNS  $\nu$  energy spectrum



SNS  $\nu$  time distribution



# The COHERENT Collaboration



~80 members,  
~20 institutions  
4 countries

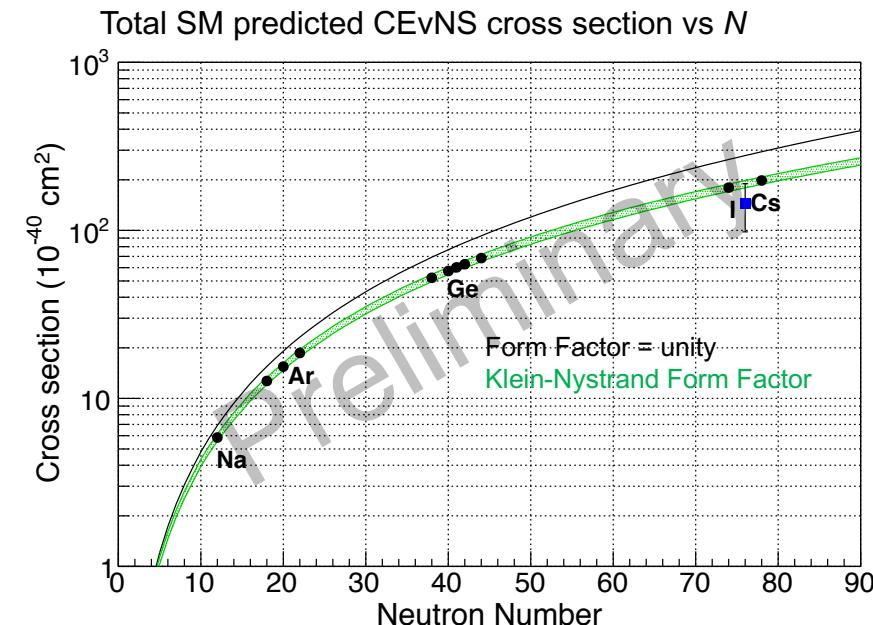
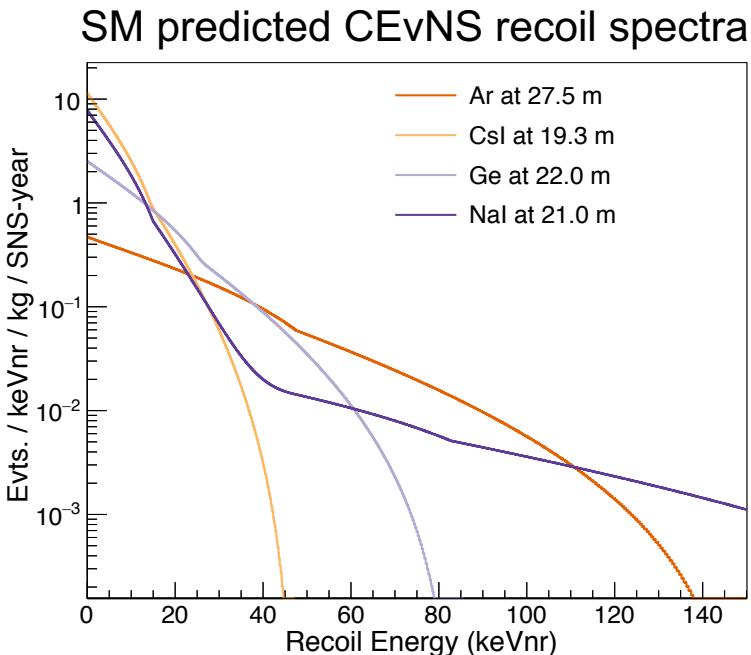


<http://coherent.ornl.gov/>



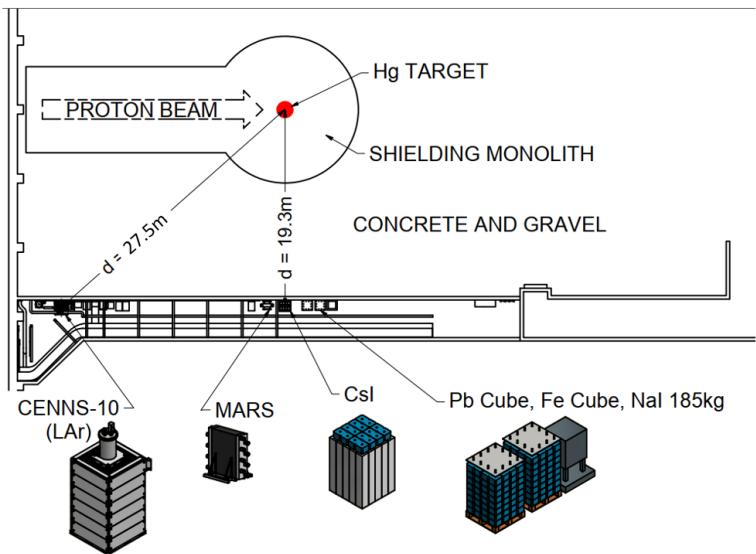
# The COHERENT Collaboration

- First goal to observe CEvNS and measure  $N^2$  dependence of CEvNS cross section via multiple targets



# COHERENT at the SNS

- Location in basement of SNS target building (“Neutrino Alley”)
  - 19-28 meters from Hg target
  - A lot of hard work went into this location by demonstrating low backgrounds



Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil Threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
Ge	HPGe PPC	16	20	2-2.5
LAr	Single-phase	24	27.5	20
NaI[Tl]	Scintillating crystal	185*/3338	28	13

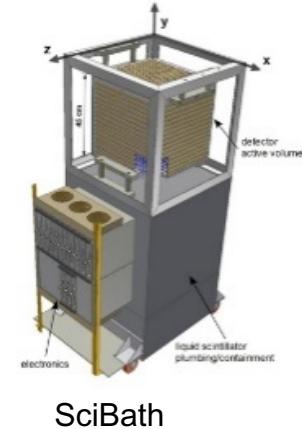


# Neutron Background Measurements

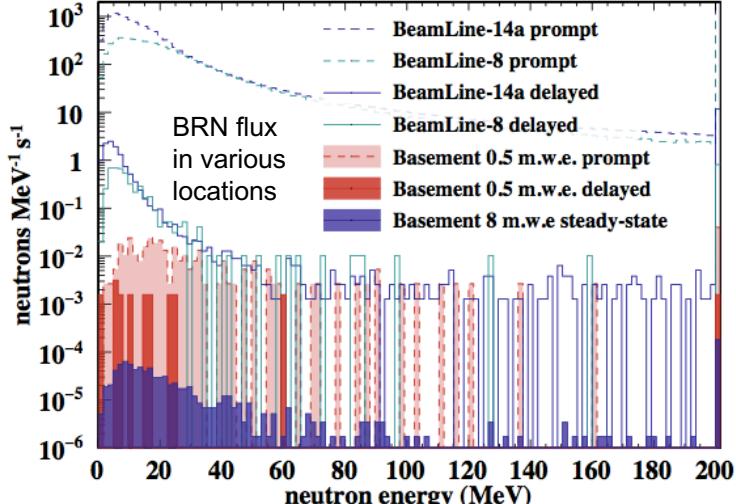
- Neutrons produced by proton colliding with the target are problematic for CEvNS measurement (beam related neutrons)
  - Mimic CEvNS signal and are in time with the beam!
  - Neutrino Alley at 8 m.w.e overburden
    - 19-28 m steel+concrete shielding from target
  - Beam related neutron (BRN) background measured across hallway with several detectors
    - MARS – Sandia
    - Sandia “Neutron Scatter Camera”
    - IU SciBath detector - at CENNS-10 location
    - Many orders of magnitude lower in Neutrino Alley than in neutron scattering experiment beamlines



Sandia “Neutron Scatter Camera”

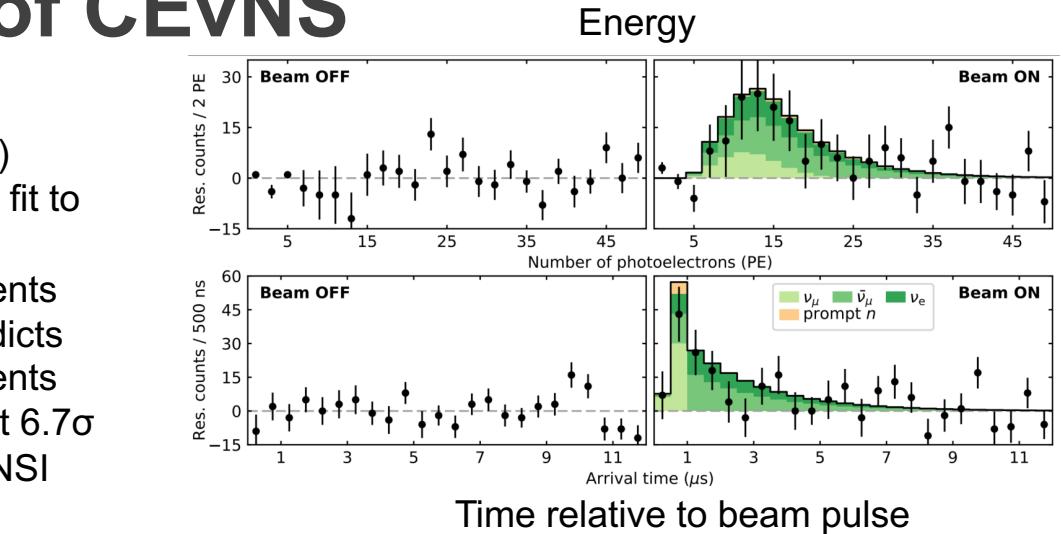


SciBath

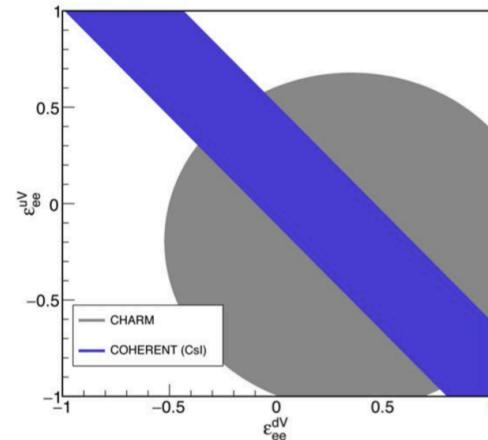
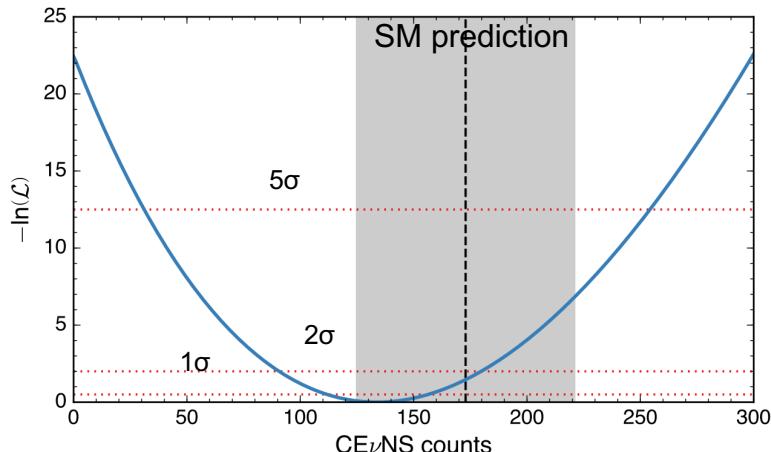


# Discovery of CEvNS

- 14.6 kg CsI crystal
- 2D (energy and time)
- Maximum Likelihood fit to data gives:
- $134 \pm 22$  CEvNS events
- Standard model predicts  $173 \pm 48$  CEvNS events
- Null result rejected at  $6.7\sigma$
- New constraints on NSI
- More data available



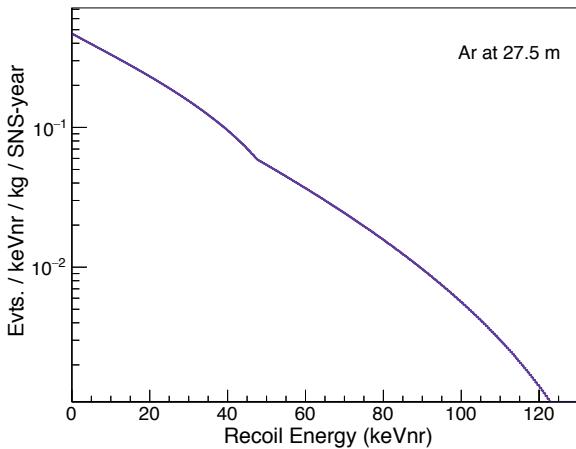
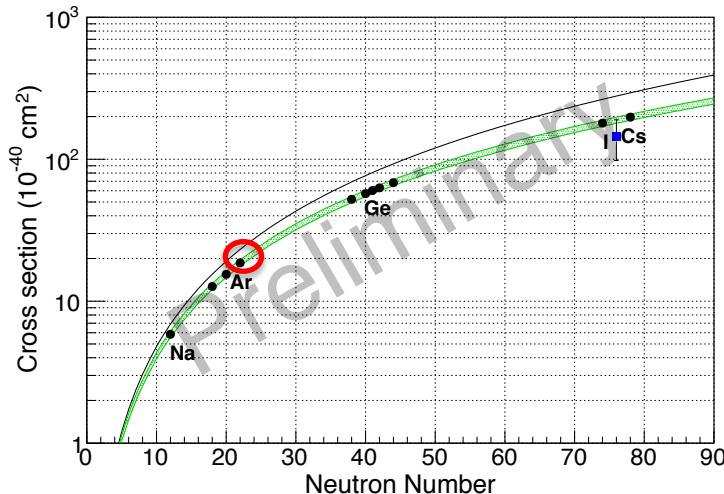
[10.1126/science.aao0990](https://doi.org/10.1126/science.aao0990)



# **CENNS-10 Detector and First detection of CEvNS on Ar target**

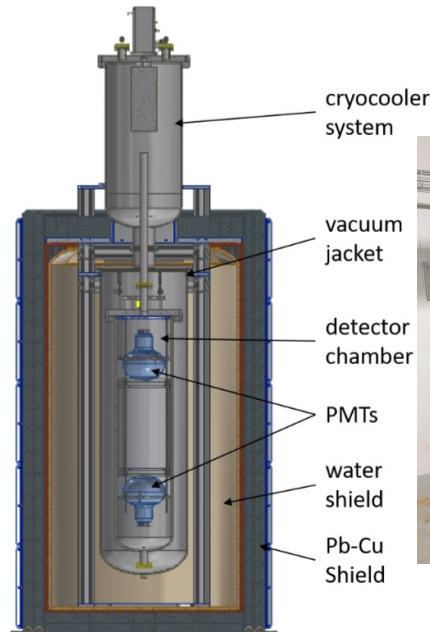
# Liquid Argon (LAr) for CEvNS

- Low N nucleus for CEvNS measurement
  - Map out  $N^2$  dependence of CEvNS cross section after CsI measurement
- Large scintillation yield of 40 photons/keVee
  - Scintillation light at 128 nm, need wavelength shifter
- Well-measured quenching factor
- Pulse shape discrimination (PSD)/Particle ID (PID) capabilities for nuclear/electron recoil separation
  - $\sim 6$  ns singlet light
  - $\sim 1.6 \mu\text{s}$  triplet light
  - Electron recoil (ER) events mostly triplet light, Nuclear recoil (NR) events mostly singlet light

Total SM predicted CEvNS cross section vs  $N$ 

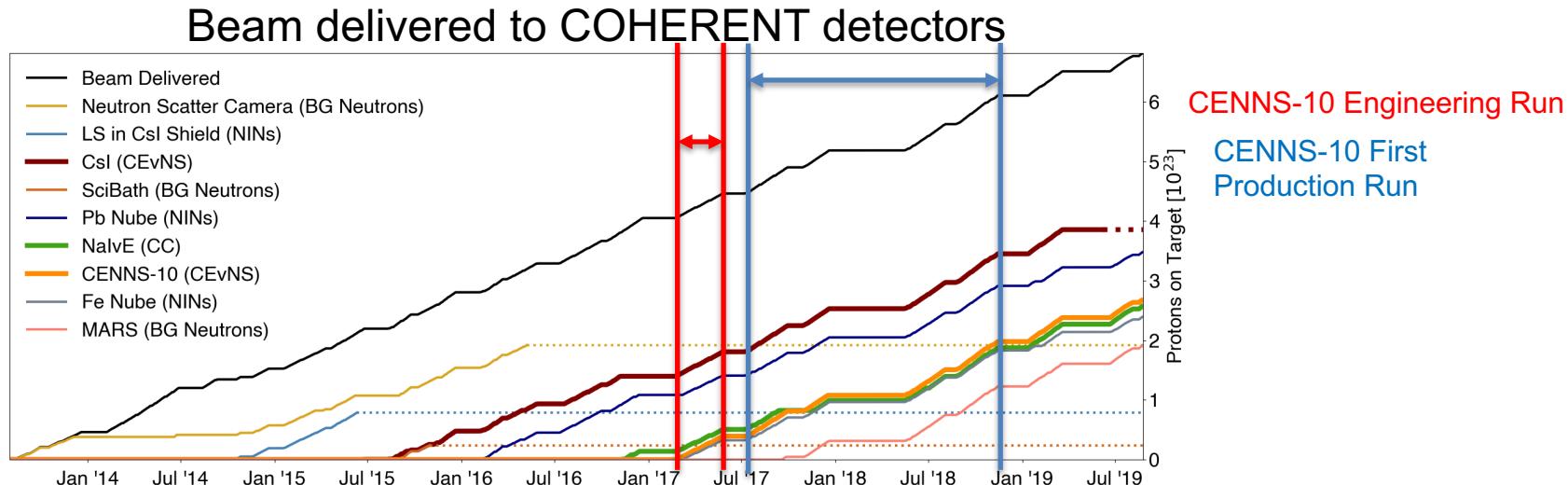
# The CENNS-10 Detector

- Originally built in 2012-2014 by J. Yoo et al. at Fermilab for CENNS effort at Fermilab
  - Thanks to A. Lathrop, R. Flores, R. Schmitt, R. Davila, D. Butler, and L. Harbacek for help on construction, design, and review!
- Moved to the SNS for use in COHERENT late 2016 after upgrades at IU and additional of substantial shielding and infrastructure at the SNS
- 24 kg fiducial volume
- 2x 8" Hamamatsu PMTs, 18% QE at 400 nm
- Tetraphenyl butadiene (TPB) coated side reflectors/PMTs
- 10 cm Pb/ 1.25 cm Cu/ 20 cm H<sub>2</sub>O shielding
- Engineering Run (early 2017): high threshold, no lead shielding, blind analysis finished, published results ([Phys. Rev. D100 \(2019\) no.11, 115020](#))
- First Production Run (July 2017-December 2018): improved threshold, blind analysis with two parallel groups finished, publication expected in very near future



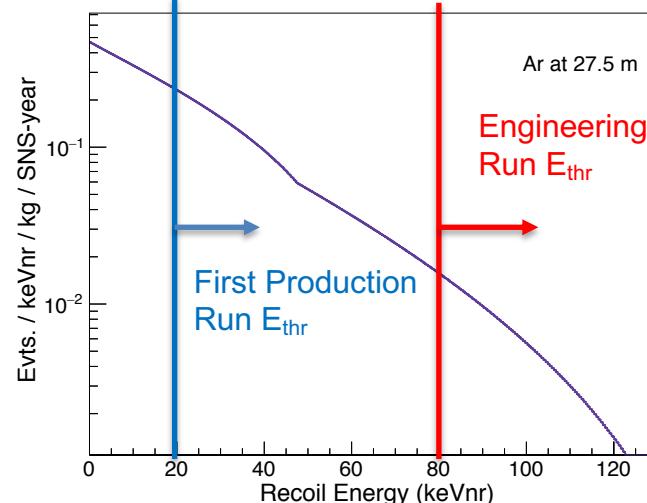
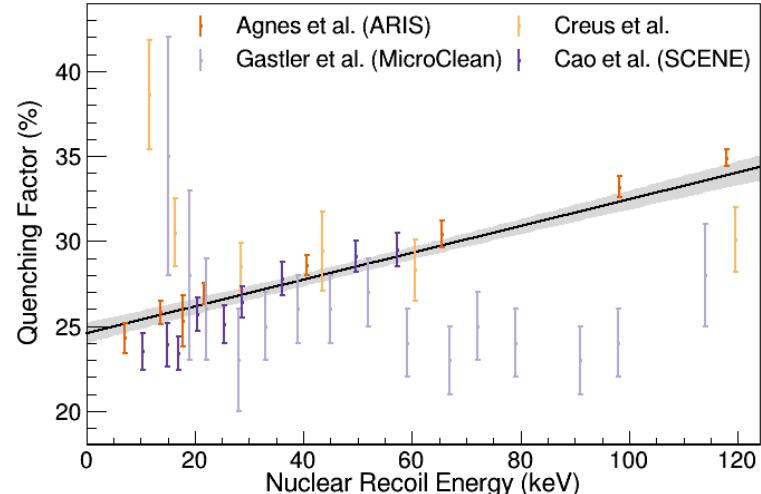
# CENNS-10 Data Collection

- Engineering Run of total 1.8 GWhr ( $\sim 0.4 \times 10^{23}$  POT) of integrated beam power from February-May 2017
- Data set considered for first physics result (First Production Run) reported here is total 6.1 GWhr ( $\sim 1.4 \times 10^{23}$  POT) of integrated beam power from July 2017-November 2018



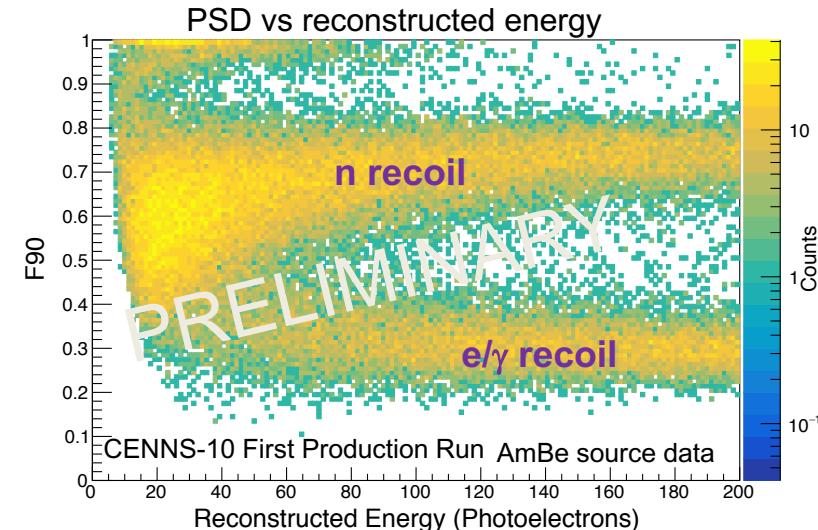
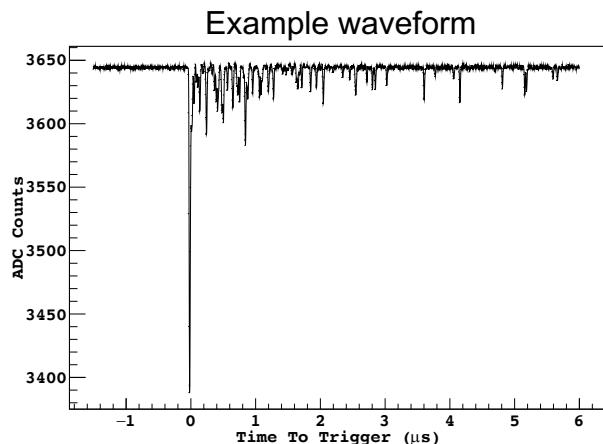
# LAr Quenching Factor

- Measurement of ratio of measured energy deposited from a nuclear recoil to measured energy deposited by an electron recoil at known energy
- Multiple measurements of LAr quenching factor in CEvNS region of interest
- Linear model fit to literature data over recoil energy range of 0-125 keVnr
  - 2% average relative uncertainty on quenching factor value in region of interest (ROI) from 0-125 keVnr
- Provides conversion from keVnr (nr = ‘nuclear recoil’) to keVee (ee = ‘electron equivalent’)



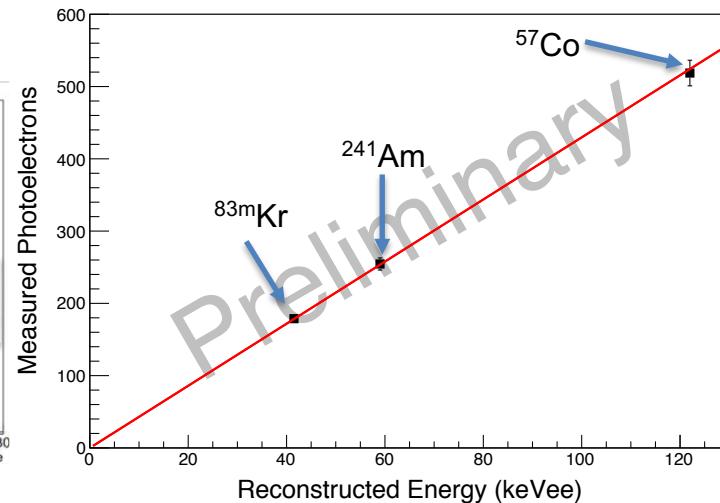
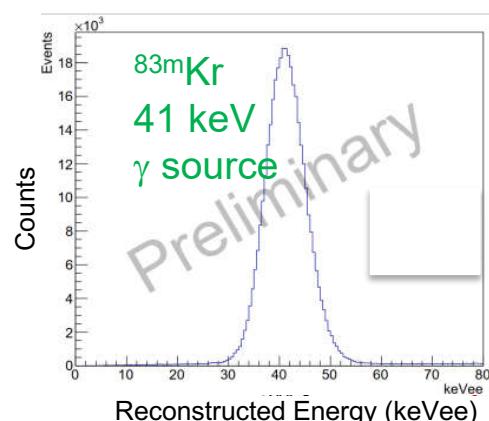
# CENNS-10 Analysis Overview

- Read out 33  $\mu\text{s}$  around each beam spill (“waveforms”)
  - Apply pulse finding algorithm to find Ar interactions (“events”)
- Characterize backgrounds
  - Measure and subtract beam-unrelated backgrounds with off-beam trigger
  - Measure beam-related neutrons (BRN) with no-water shielding runs
- Place cuts in energy, pulse shape discrimination (PSD, particle ID), and time
  - Define PSD variable “F90” = fraction of light detected in first 90 ns
- Analysis result from full 3D binned likelihood analysis in energy, F90, and time



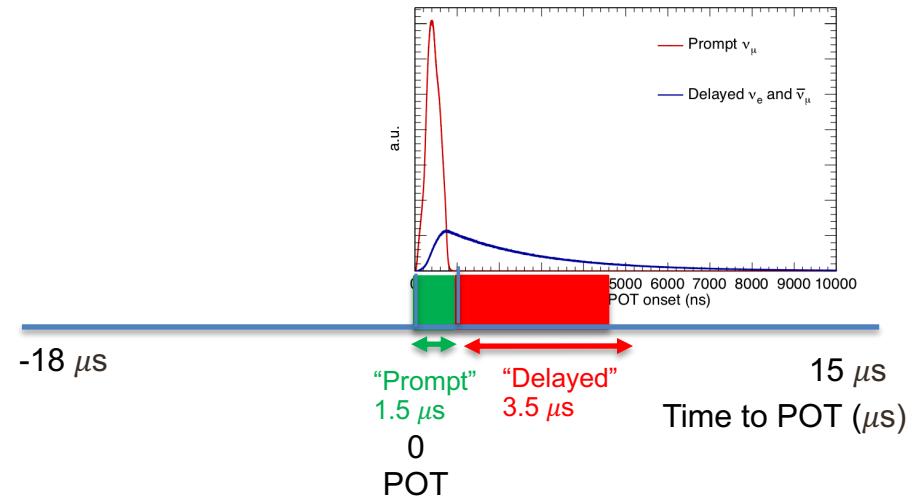
# CENNS-10 Calibration

- Calibrate detector with variety of gamma sources
  - Measured light yield:  $4.6 \pm 0.4$  photoelectrons/keVee
  - At  $^{83m}\text{Kr}$  energy (41.5 keVee), mean reconstructed energy measured to 2%
    - 9.5% energy resolution at 41.5 keVee
- Calibrate detector nuclear recoil response using AmBe source



# SNS Trigger Details

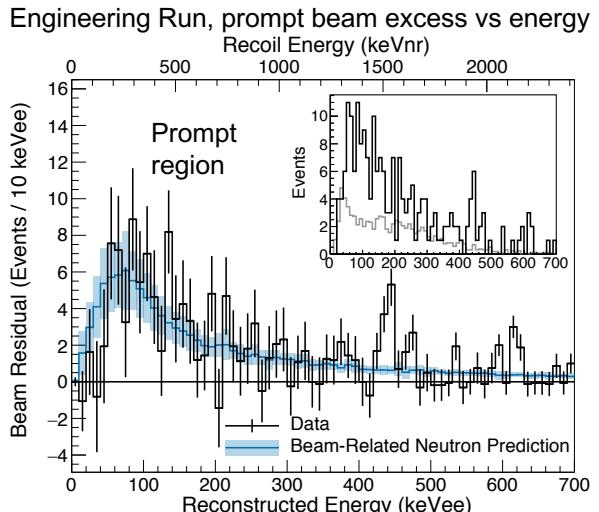
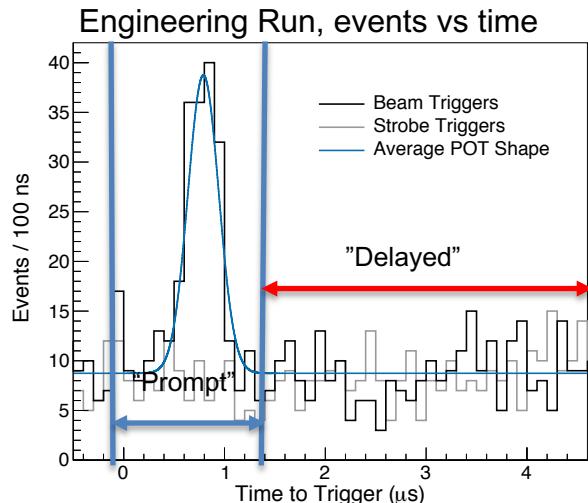
- SNS provides neutrinos in regions after protons on target (POT)
  - "Prompt": 0-1.5  $\mu$ s after POT
  - "Delayed": 1.5-5  $\mu$ s after POT
- CEvNS neutrino signal in both prompt and delayed windows
- Beam-related neutron background measured only in prompt window
  - Delayed neutron measurements consistent with zero
- Identical off-beam trigger 14 ms after accelerator trigger
  - Measure beam-unrelated backgrounds in-situ



# Neutron Background Characterization

- Data from Engineering Run, analysis of 1.8 GWhr of SNS beam data from February-May 2017
- TPB coated acrylic backed by Teflon reflector and TPB coated acrylic disk
- Threshold (80 keVnr) not low enough for sensitive CEvNS search
- Optimized cuts based on signal/noise
- Beam-related excess consistent with previous measurements/simulations
  - Delayed window excess consistent with zero due to high threshold and small beam sample
  - Use to constrain prompt beam-related neutron backgrounds for First Production Run
- Also, place limit on CEvNS cross section

Engineering Run Results:  
[Phys. Rev. D100 \(2019\) no.11, 115020](#)  
[M. R. Heath \(IU PhD Thesis\) \(2019\)](#)  
<http://inspirehep.net/record/1744690?ln=en>  
PRD Editor's Suggestion

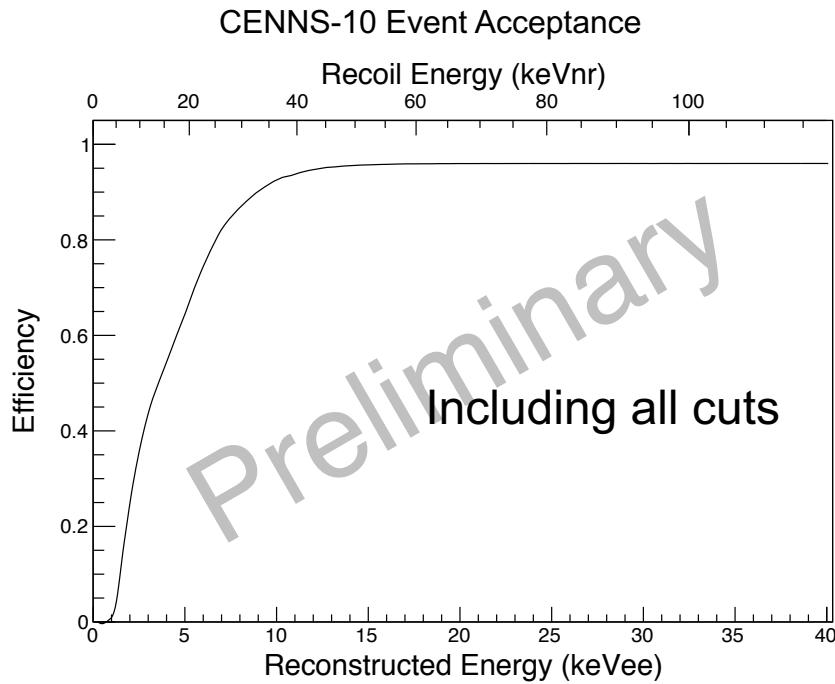


# Parallel Blind Analyses

- Two groups performed independent analysis of CENNS-10 First Production Run
  - To lessen potential bias on result during analysis procedure
    - e.g. we know SM prediction
  - US-based and Moscow-based groups
  - SNS beam-on data were not seen until cuts finalized
  - No cut-values or results shared between groups before data opening
  - Will focus on US analysis in this talk

# Event Selection

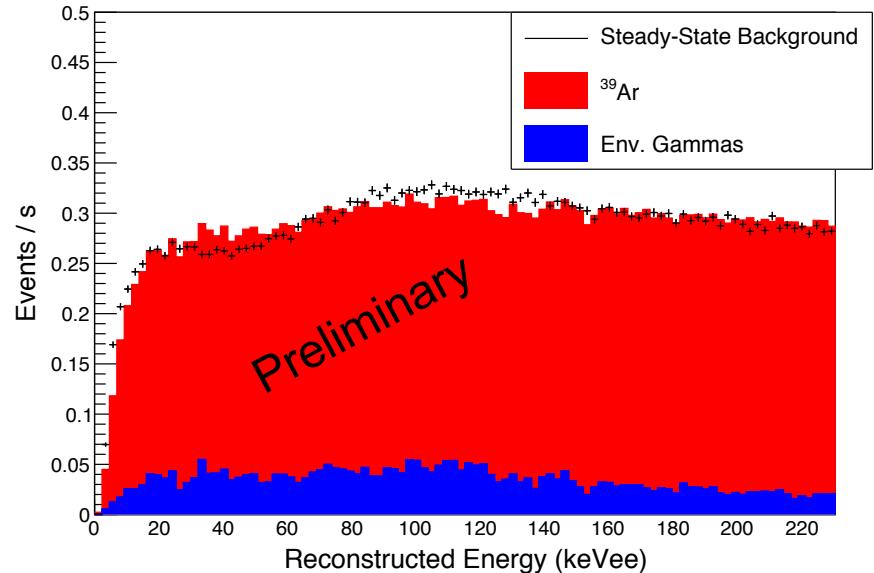
- Waveform/Event quality cuts
  - Baseline, Saturation, Pile-up
    - >96% of events pass
  - Candidate events
    - Threshold (>2 photoelectrons seen in both PMTs)
    - Apply energy, time, pulse shape discrimination (PSD) cuts



# Beam-Unrelated Backgrounds

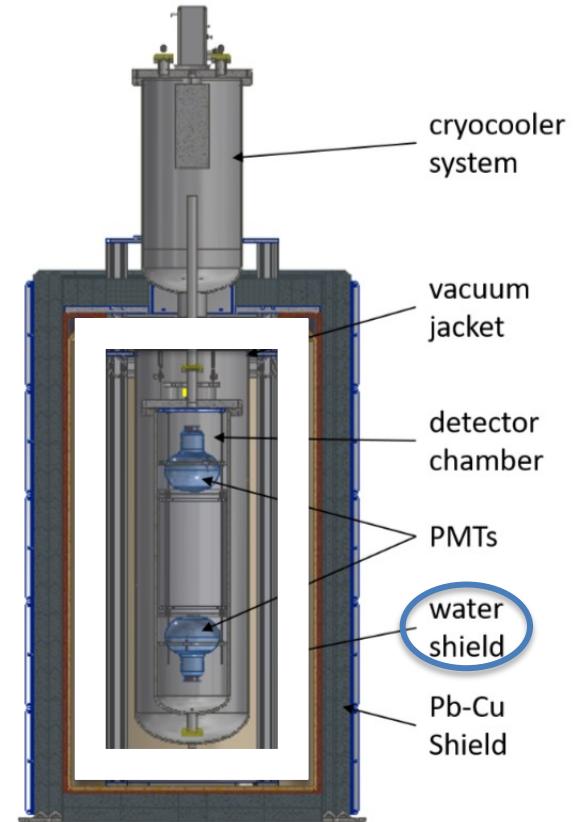
- Main beam-unrelated background is  $^{39}\text{Ar}$  with full shielding
- Directly measured through off-beam triggers
- Large statistical errors remain after the background subtraction

CENNS-10 beam-unrelated background energy spectrum



# Beam-Related Neutrons (BRN)

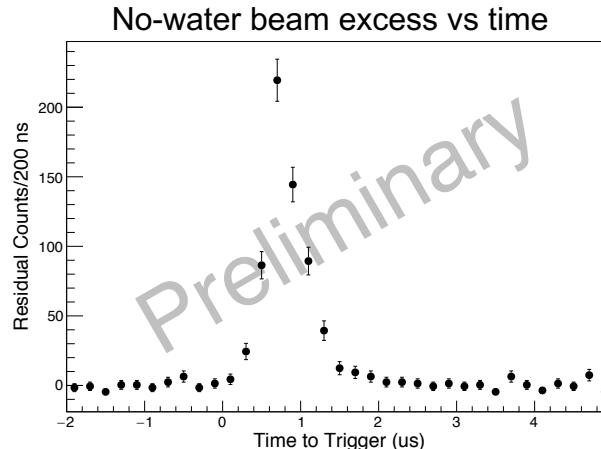
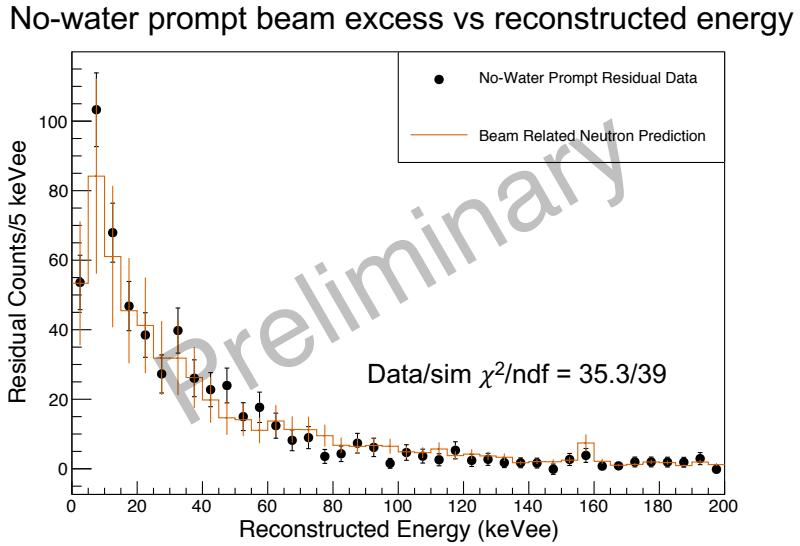
- Beam related neutron normalization from no-water shielding data
  - Remove 20 cm water shielding by emptying water tank
  - 0.54 GWhr integrated beam power of no-water shielding data
  - Predicted flux input to MC comes from external flux measurement at CENNS-10 location
    - Using IU built SciBath detector
- Scale MC for full-shielding with data/MC ratio from no-water
  - Only rely on MC to transport neutrons through water shield



# Beam-Related Neutrons (BRN)

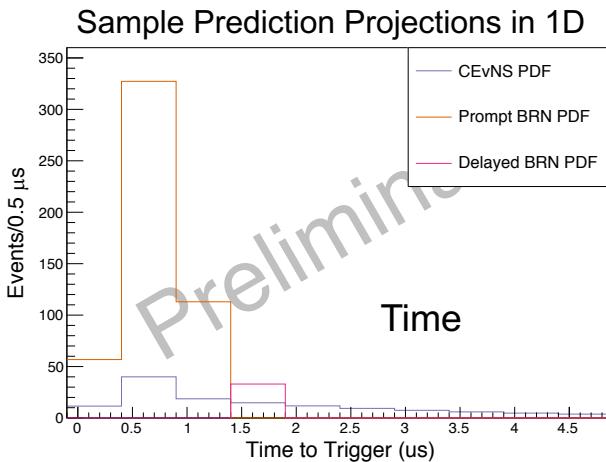
- Compare beam-unrelated background subtracted excess in energy with MC prediction
  - Good energy shape agreement
- Normalization constraints come from measured Engineering Run rates
  - 30% prior uncertainty on the beam-related neutron normalization to reflect uncertainty in procedure
- Energy shape not sensitive to errors in quenching factor or flux shape
- Beam-related neutron predictions in time set by this measurement

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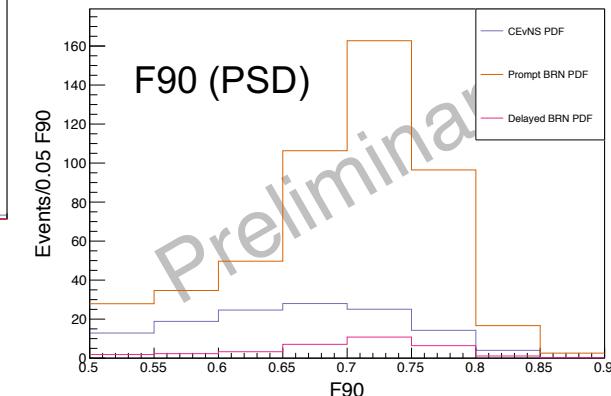
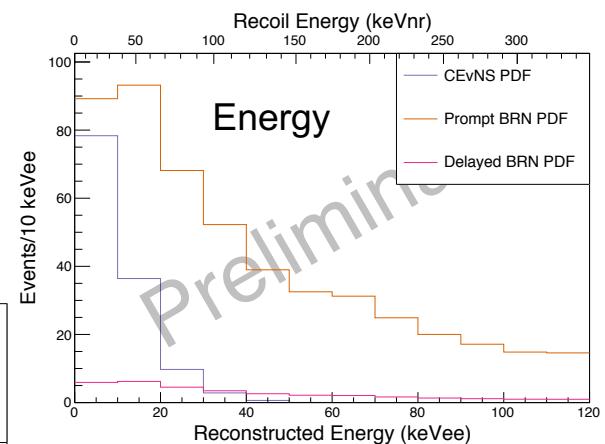
# Predicted Event Distributions for Likelihood Analysis

- Perform 3D binned likelihood analysis in energy, F90, and time
- Waveform/event quality cuts
- 0-120 keVee energy range
- 0.5-0.9 F90 range
- -0.1-4.9  $\mu$ s time to trigger range
- 960 total bins
- PDFs determined from CEvNS, beam-related neutron predictions
  - Beam-unrelated background determined from oversampling of data in off-beam window
  - Fit will further constrain background rates



Sample Predictions

Predicted SM CEvNS	$128 \pm 17$
Predicted Beam Related Neutrons	$497 \pm 160$
Predicted Beam Unrelated Background	$3154 \pm 25$
Predicted Late Beam Related Neutrons	$33 \pm 33$



# Systematic Errors

- For 3D likelihood analysis, need to further consider changes to energy, time, F90 spectra
  - Significant errors listed in lower table are those that change the PDF shape substantially
  - Additional systematics that effect the fit CEvNS rate are:
    - CEvNS: F90, timing profile
    - Beam-related neutrons: energy, timing profile

CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
Prompt Light Fraction	7.8%
Fiducial Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

Additional Likelihood Fit Shape-Related Errors	
Error Source	Fit Event Uncertainty
CEvNS Prompt Light Fraction	4.5%
CEvNS Arrival Mean Time	2.7%
Beam Related Neutron Energy Shape	5.8%
Beam Related Neutron Arrival Time Mean	1.3%
Beam Related Neutron Arrival Time Width	3.1%
Total Error	8.5%

**Then the data was opened!**

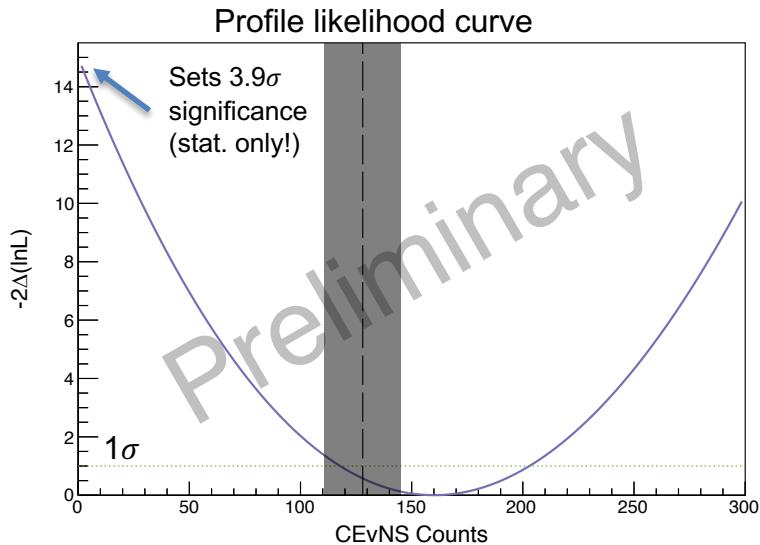
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# Likelihood Fit Results

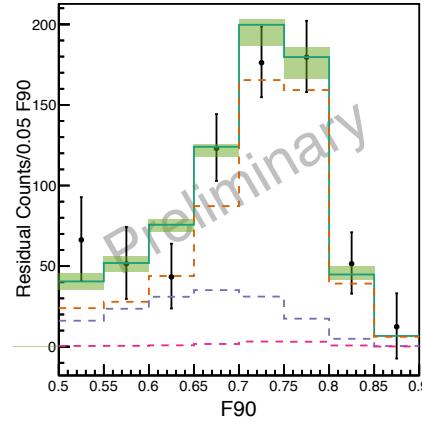
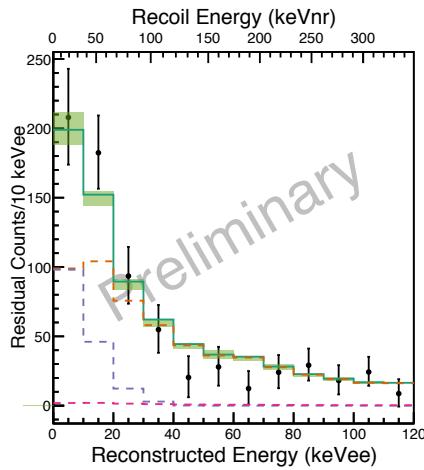
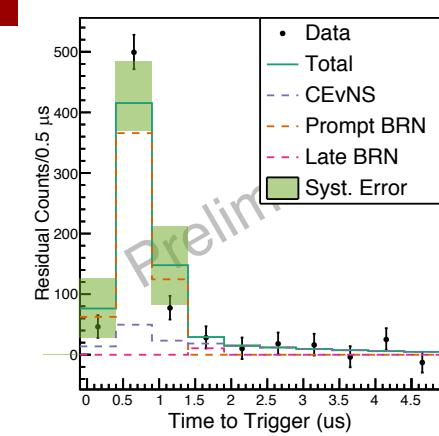
- 3D binned likelihood analysis in energy, F90, time space
  - Include both prompt and delayed time regions
- Best fit CEvNS counts of  $159 \pm 43$  (stat.)  $\pm 14$  (syst.)
  - Result (stat. only) rejects null hypothesis at  $3.9\sigma$
  - Result (stat. + syst.) rejects null hypothesis at  $3.5\sigma$
  - Best fit result within  $1\sigma$  of SM prediction
  - Wilks' Theorem checked with fake data

Predicted SM CEvNS	$128 \pm 17$
Predicted Beam Related Neutrons	$497 \pm 160$
Predicted Beam Unrelated Background	$3154 \pm 25$
Predicted Late Beam Related Neutrons	$33 \pm 33$

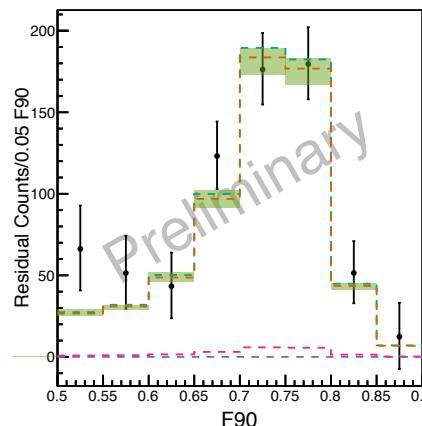
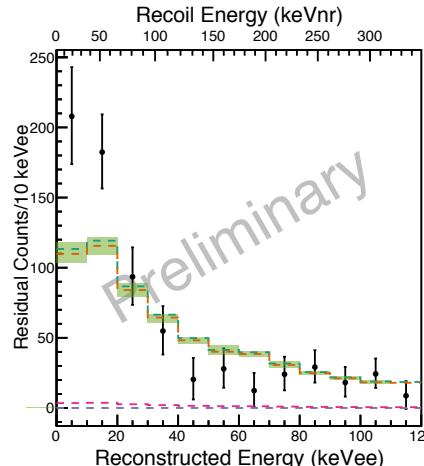
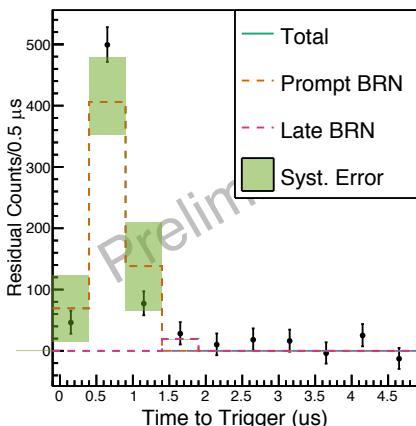
Data Events	3752
Fit CEvNS	$159 \pm 43$ (stat.) $\pm 14$ (syst.)
Fit Beam Related Neutrons	$553 \pm 34$
Fit Beam Unrelated Background	$3131 \pm 23$
Fit Late Beam Related Neutrons	$10 \pm 11$
$2\Delta(-\ln L)$	15.0
Null Rejection Significance	$3.5\sigma$ (stat. + syst.)



# Spectra and Comparison with Null Hypothesis



Top Left: Prompt+delayed region, beam unrelated background subtracted projections of 3D likelihood fit  
Bands are systematic errors calculated from 1 sigma excursions



Bottom Left: Same as above, null hypothesis fit (CEvNS = 0)

- Presence of CEvNS fits data well
- Recoil energy distribution results in poor fit without CEvNS

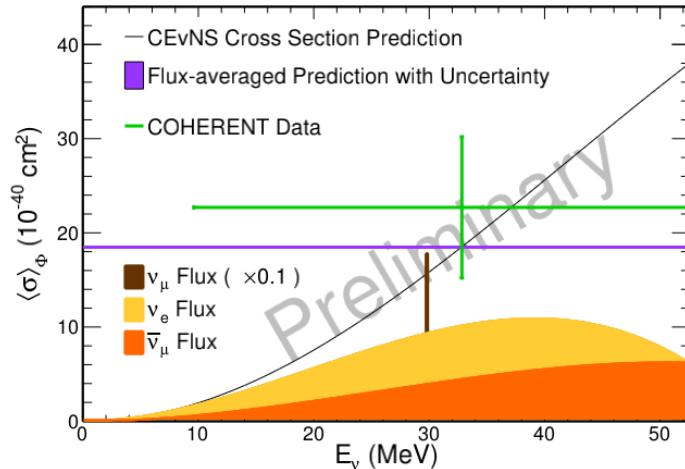
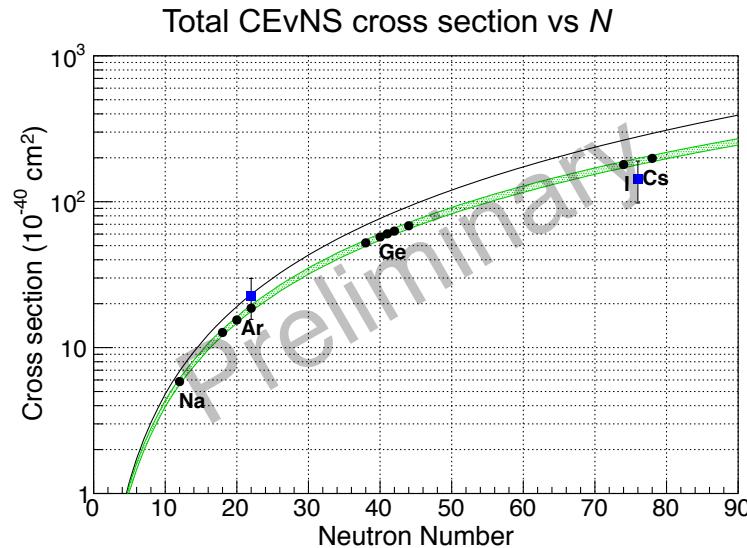
# CEvNS Cross Section

- Flux-averaged cross section
  - Compute using ratio of measured CEvNS events to predicted SM CEvNS events

$$\frac{N_{meas}}{N_{SM}} = 1.2 \pm 0.4$$

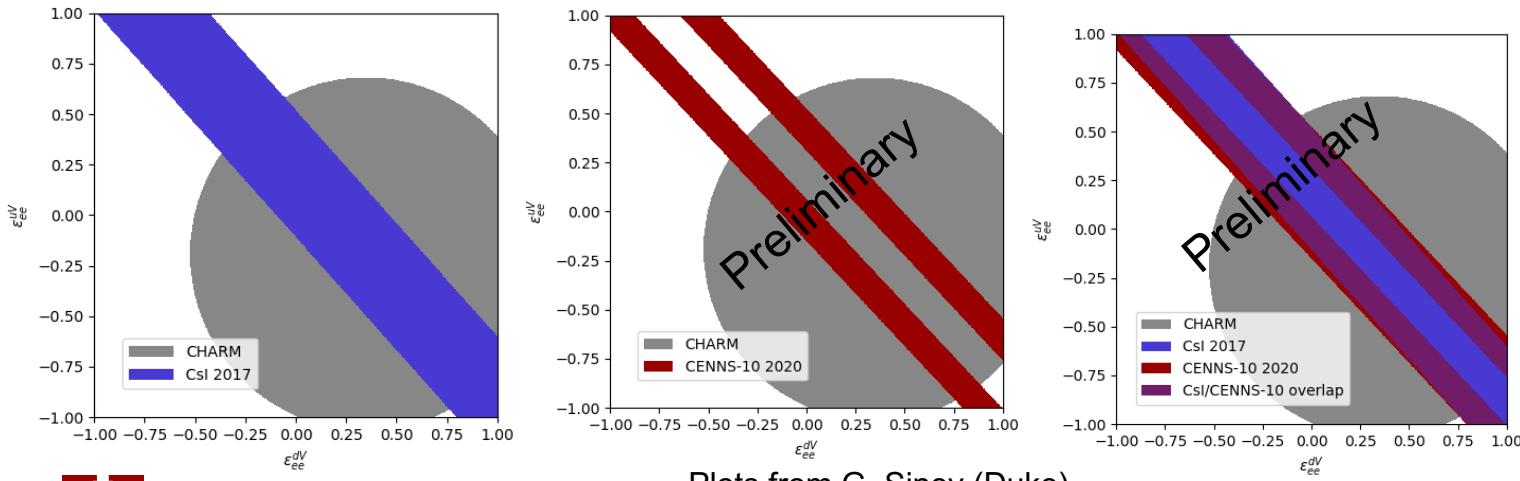
$$\sigma_{meas} = \frac{N_{meas}}{N_s \phi \epsilon} = (2.3 \pm 0.7) \times 10^{-39} \text{ cm}^2$$

- Error on  $\sigma_{meas}$  dominated by statistical error on  $N_{meas}$
- Additional systematics from fit systematics and on  $N_s, \phi, \epsilon$  via flux, fiducial volume, efficiency errors



# Non-Standard Interactions (NSI)

- Compute allowed regions in NSI parameter space
  - Specifically  $\nu_e$  flavor-preserving quark-vector coupling parameter space
  - Set all other  $\varepsilon = 0$



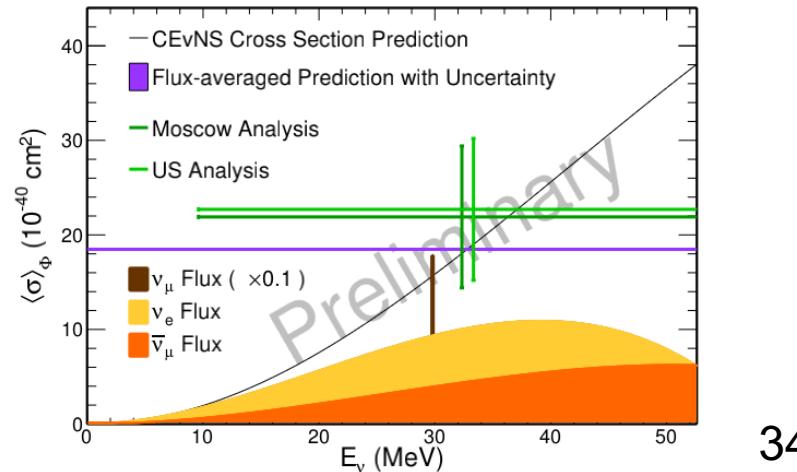
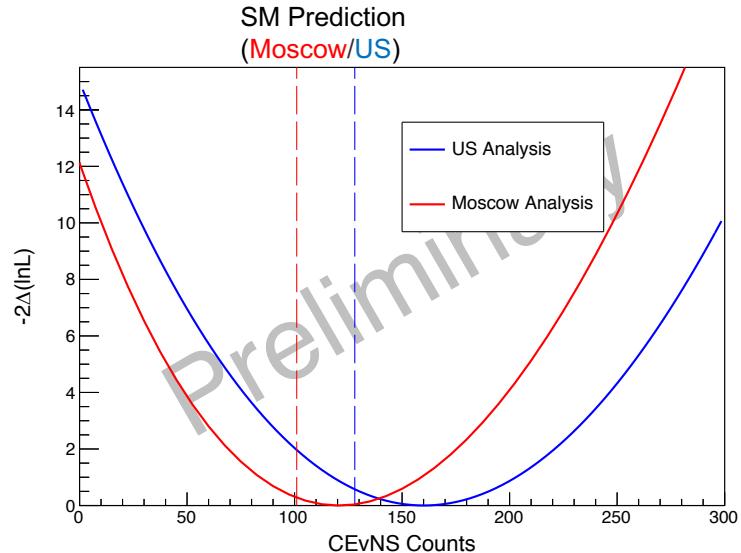
# 2-Analysis Comparison

- Moscow analysis
  - Similar 3D binned likelihood analysis performed
    - More strict selection cuts used in energy, F90
- Both analyses find significant excess of events within  $1\sigma$  of SM prediction

## Moscow analysis results

Predicted CEvNS	$101 \pm 12$
Fit CEvNS	$121 \pm 36$ (stat.) $\pm 15$ (syst.)
$2\Delta(-\ln L)$	12.1
Null Rejection Significance	$3.1\sigma$ (stat. + syst.)

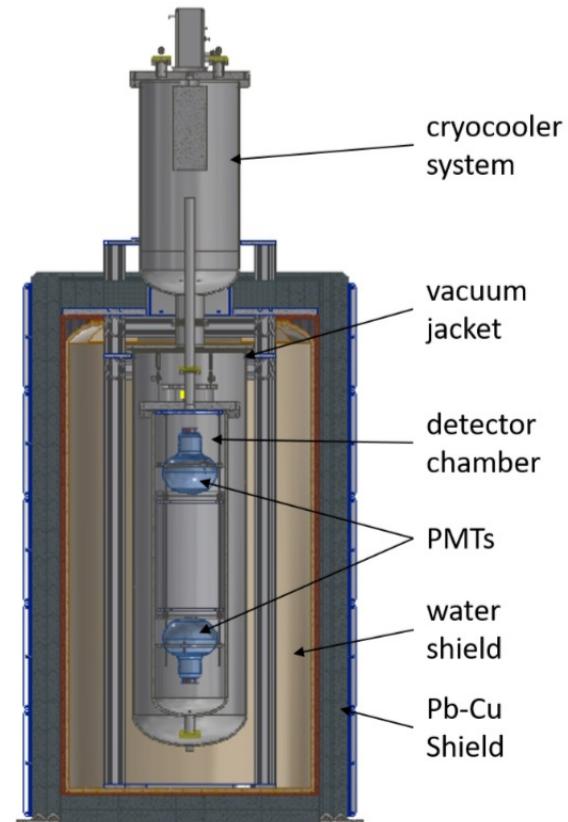
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# Future COHERENT Liquid Argon – Towards CENNS-750

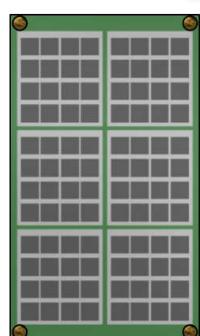
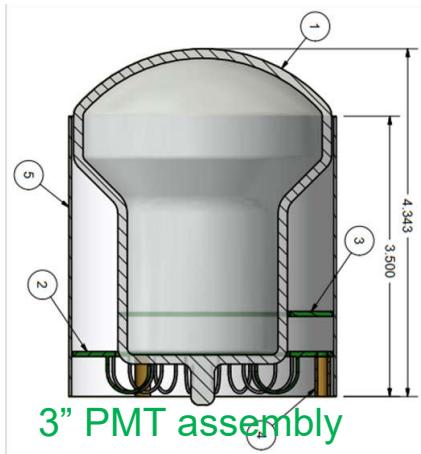
# Future CENNS-10 Activities

- Continuing physics data collection using CENNS-10
  - Additional >3 GWhr of data with additional neutron shielding installed
    - Need further neutron MC studies for analysis
- Possible considerations for CENNS-10 improvements
  - Possibility of acquiring underground Ar with lower  $^{39}\text{Ar}$  content
  - Addition of further neutron shielding in current detector location
  - Move detector to previous CsI detector location for increased neutrino flux and lower neutron backgrounds
- R&D vessel to test Xe doping in LAr, photodetectors, wavelength shifters for ton-scale detector CENNS-750

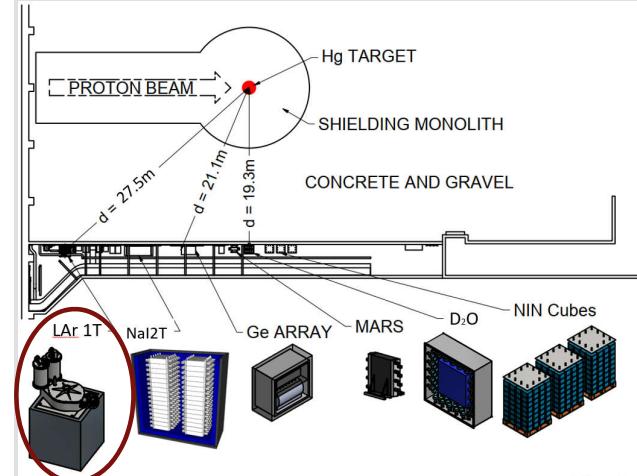


# CENNS-750

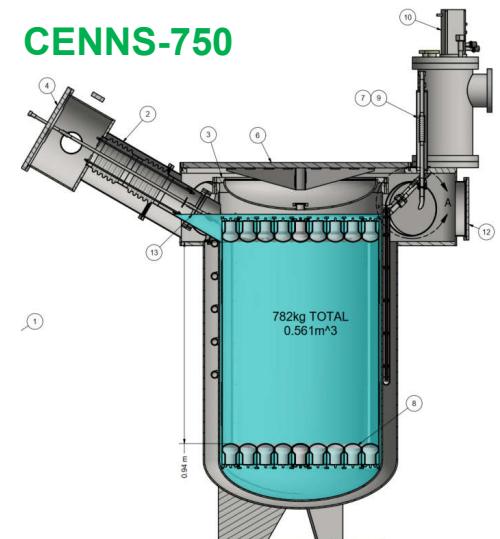
- Single-phase LAr calorimeter, 610 kg fiducial mass
- Leverage successful operation of CENNS-10
  - Expect ~20 keVnr threshold in ~25x LAr volume, push for lower
- 3" PMTs or VUV/visible silicon photomultipliers (SiPMs)
  - Investigate optimal wavelength shifting scheme
  - Ongoing testing at IU/ORNL



SiPM assembly

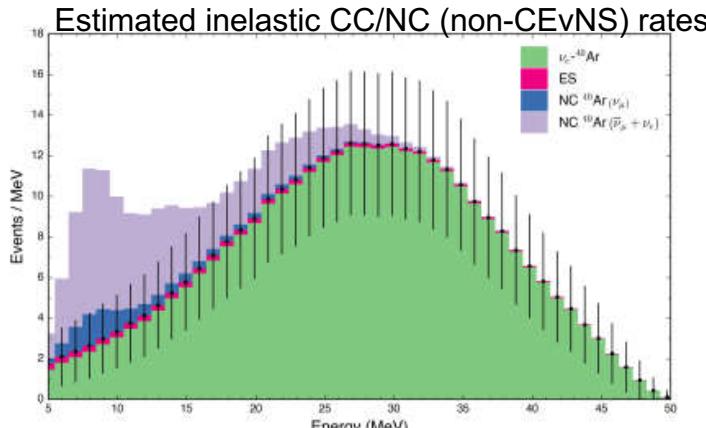


CENNS-750

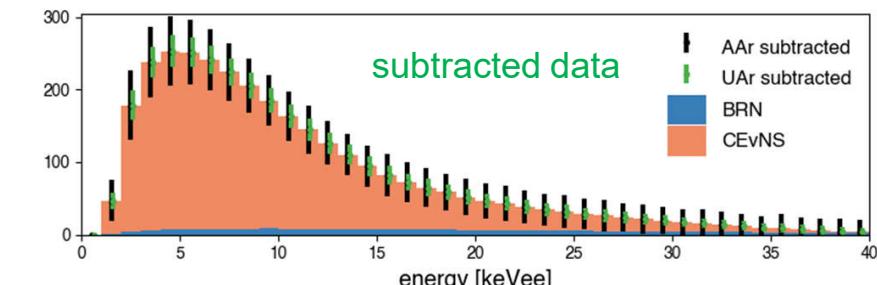
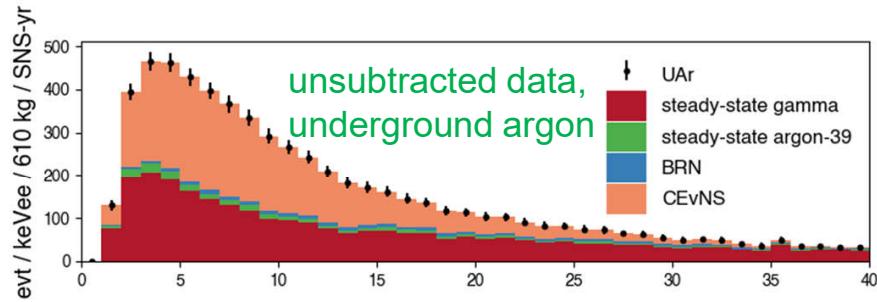
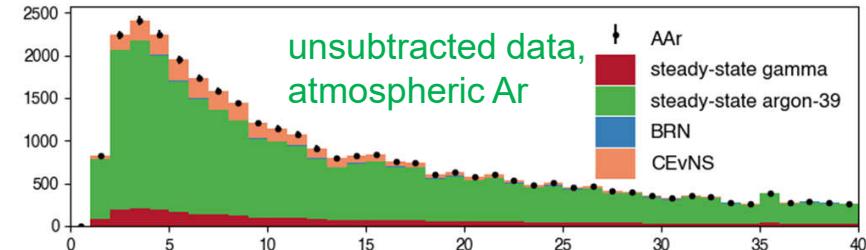


# Precision Physics with CENNS-750

- ~3000 CEvNS events/SNS-year
- ~400 inelastic charged/neutral current (CC/NC) events/SNS-year
  - Important for DUNE low-energy physics program!



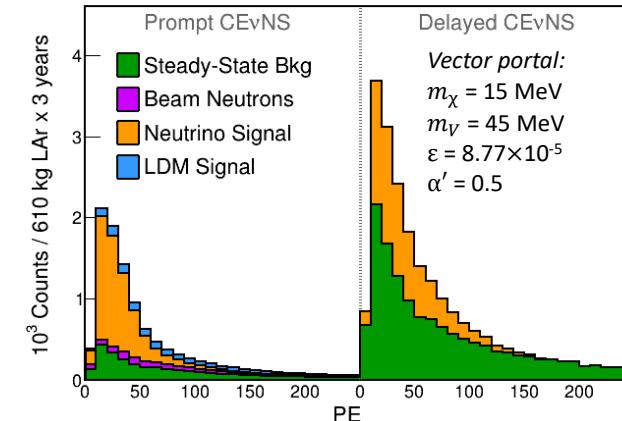
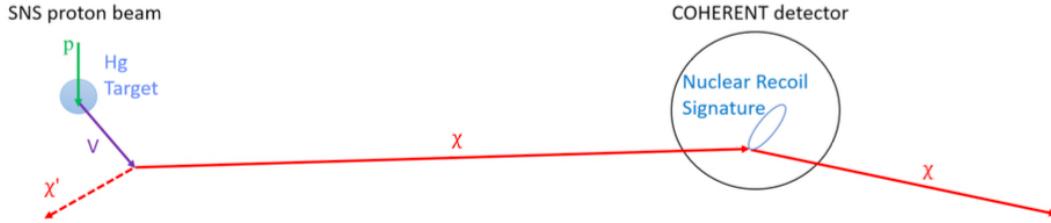
CEvNS/bkg predictions with CENNS-750



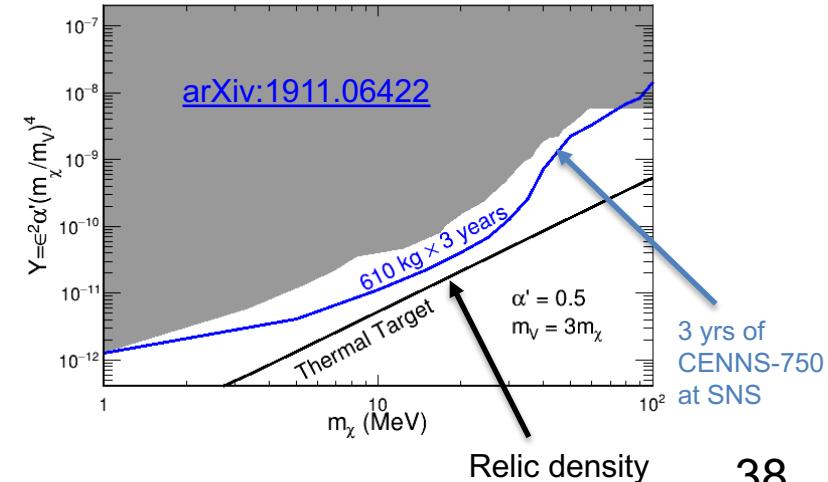
$$\nu_e + {}^{40}\text{Ar} \rightarrow \text{e}^- + {}^{40}\text{K} \quad (\text{CC}) \quad \nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar} \quad (\text{NC})$$

# Precision Physics with CENNS-750

- CENNS-750 places strong limits on vector portal accelerator-produced light dark matter
  - Produced in p-Hg collisions at SNS
    - $\pi^0$  decay into dark matter
    - Interaction identical to CEvNS
  - Dark matter signal is excess over CEvNS signal
    - CEvNS is a background!
    - Understanding/reduction of beam-related neutrons important!

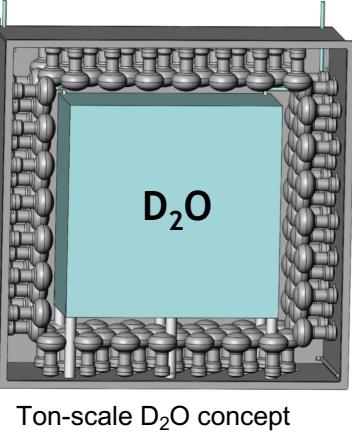
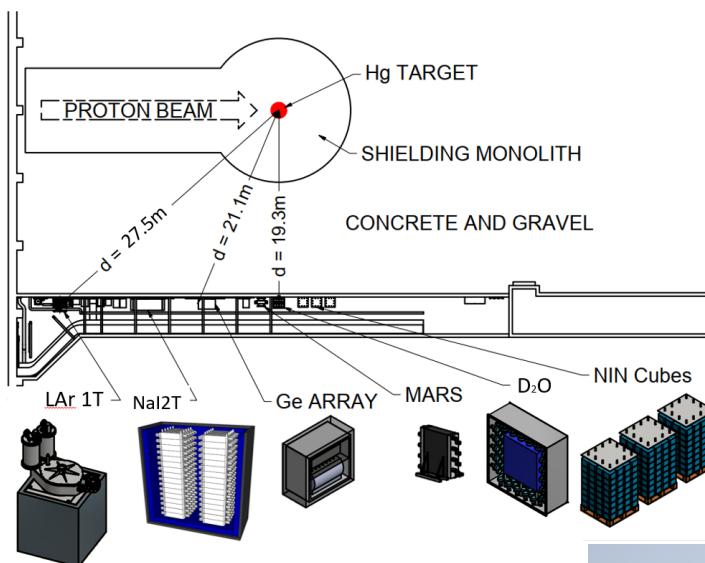


Plots from D. Pershey (Duke)

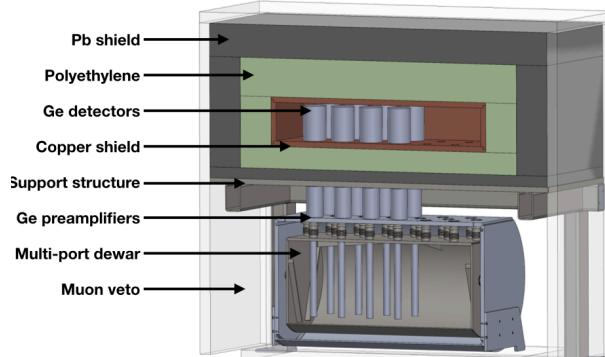


# Other Future COHERENT Efforts

- 16 kg of HPGe detectors for CEvNS measurement
- Ton-scale NaI[Tl] detector array for simultaneous CEvNS/ $^{127}\text{I}$  charged current measurements
- Ton-scale D<sub>2</sub>O Cherenkov detector to reduce neutrino flux uncertainty
  - $\nu_e$ -d charged current cross section theoretically known to 2-3%



Ton-scale D<sub>2</sub>O concept

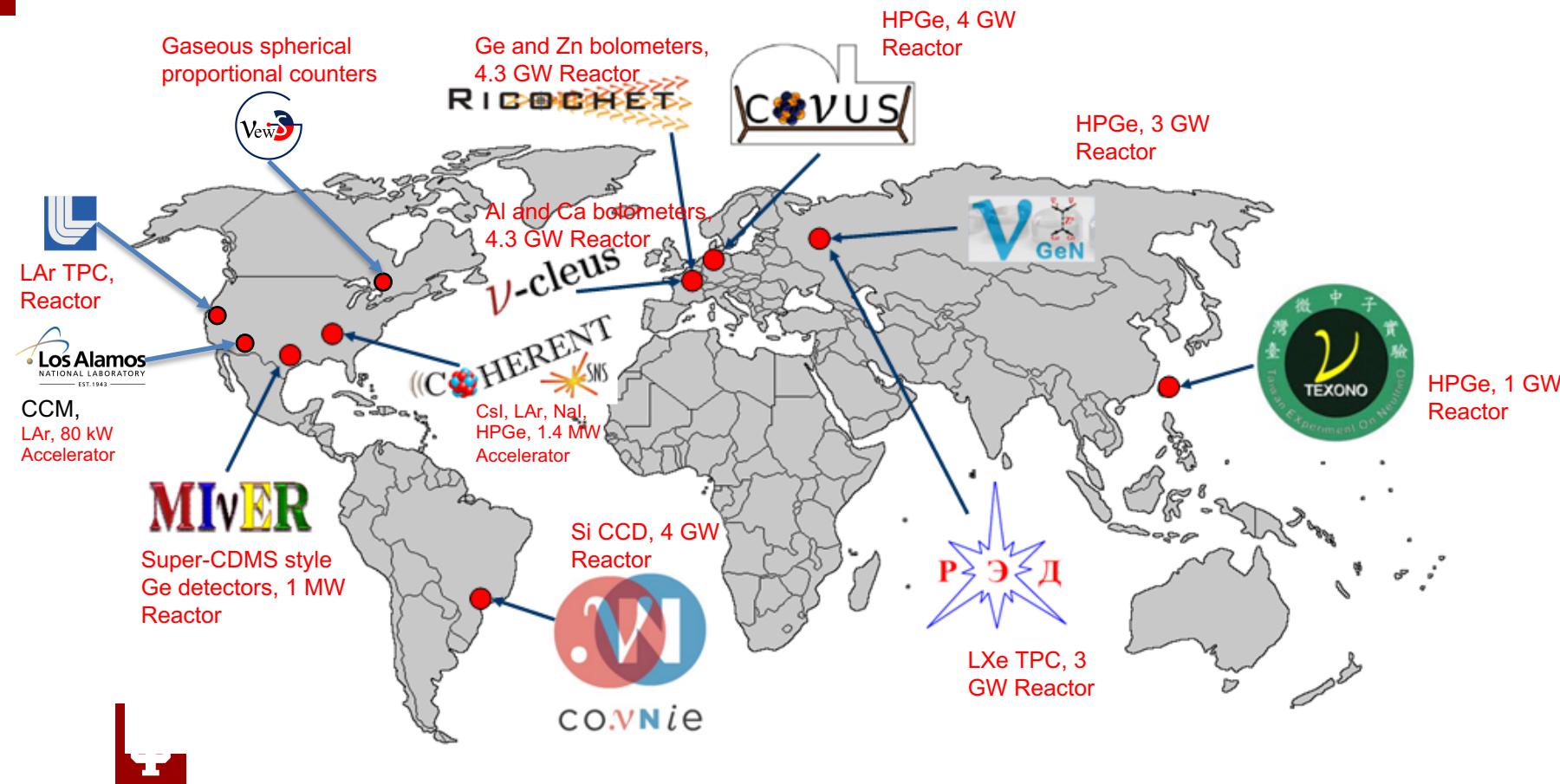


COHERENT Ge conceptual design



Modular ton-scale NaI[Tl] concept

# CEvNS Around the World

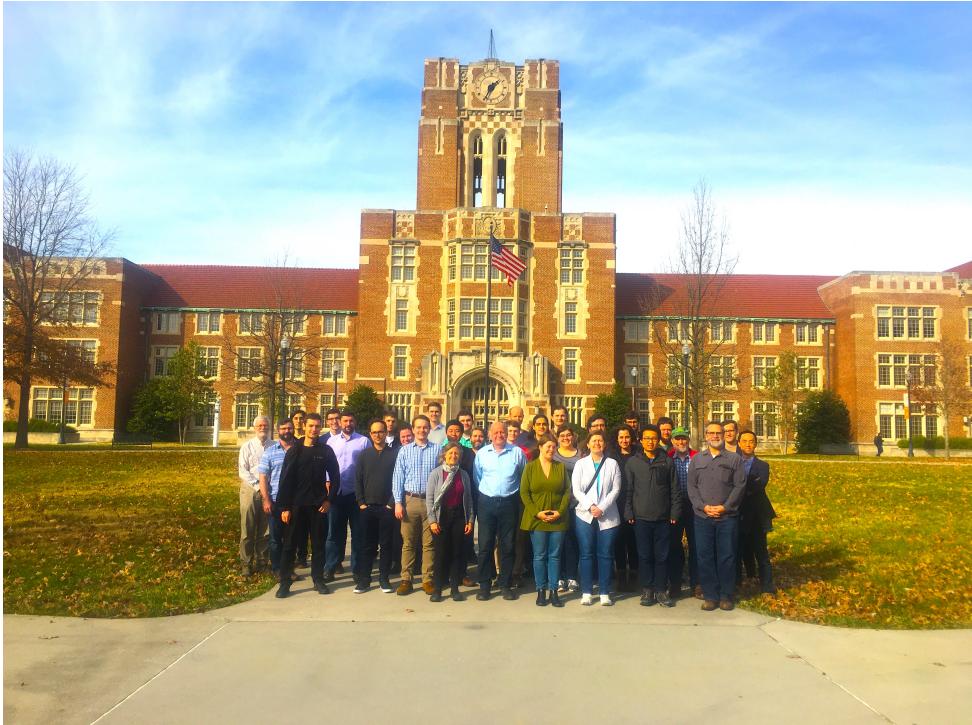


# Summary



- CEvNS is a tool to access a host of fundamental physics topics
- The COHERENT experiment at the SNS has a rich program to measure CEvNS after first detection in 2017
- First low N measurement of CEvNS on  $^{40}\text{Ar}$  with CENNS-10 detector
  - Thanks to Fermilab for the continued loan of the CENNS-10 detector!
  - $3.5\sigma$  observation of CEvNS in  $^{40}\text{Ar}$  with first production data!
- COHERENT has a robust suite of future experiments, including Ge, NaI, and a ton-scale LAr detector CENNS-750

# Thank you! Questions?



<http://coherent.ornl.gov/>



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